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CONTRIBUTIONS OF THE FLUID MODELING FACILITY TO EPA's COMPLEX TERRAIN MODEL DEVELOPMENT PROGRAM

by

WILLIAM H. SNYDER

Meteorology and Assessment Division
Atmospheric Sciences Research Laboratory
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

Atmospheric Sciences Research Laboratory
Office of Research and Development
U.S. Environmental Protection Agency
Research Triangle Park, NC 27711

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The author, William H. Snyder, is a physical scientist in the Meteorology and Assessment Division, Atmospheric Sciences Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, NC. He is on assignment from the National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

FORWARD

The Atmospheric Sciences Research Laboratory (ASRL) conducts intramural and extramural research programs in the physical sciences to detect, define, and quantify air pollution and its effects on urban, regional, and global atmospheres and the subsequent impact on water quality and land use. The Laboratory is responsible for planning, implementing, and managing research and development programs designed to quantify the relationships between emissions of pollutants for all types of sources with air quality and atmospheric effects, and to uncover and characterize hitherto unidentified air pollution problems. Information from ASRL programs and from the programs of other government agencies, private industry, and the academic community are integrated by the Laboratory to develop the technical basis for air pollution control strategies for various pollutants.

The Complex Terrain Model Development Program is designed to develop reliable atmospheric dispersion models that are applicable to large pollutant sources located in complex terrain. The major field studies of this six-year program were conducted during 1980 at Cinder Cone Butte near Boise, Idaho, during 1982 at Hogback Ridge near Farmington, New Mexico, and during 1983–84 at the Tracy Power Plant near Reno, Nevada. Data from these field studies along with measurements of fluid modeling simulations performed in the EPA Fluid Modeling Facility are being used to quantify the effects of terrain obstacles on stable plume dispersion. A series of annual milestone reports has been issued to describe the development of the Complex Terrain Dispersion Model (CTDM) and to contrast the performance evaluation of the CTDM against existing complex terrain dispersion models. This report describes the contributions of the Fluid Modeling Facility to the Complex Terrain Model Development Program.

A. H. Ellison

A.H. Ellison
Director
Atmospheric Sciences Research Laboratory

ABSTRACT

The contributions of the EPA Fluid Modeling Facility (FMF) to the Complex Terrain Model Development Program (CTMDP) are described. These contributions included a wide range of laboratory studies and a limited amount of numerical modeling of flow and diffusion in neutral and stably stratified conditions in complex terrain. The goal of the CTMDP is the development of a dispersion model valid in complex terrain, with emphasis on plume impaction on nearby hills during nighttime stable conditions. Work at the FMF prior to the inception of the program provided the basic framework for the model – the dividing–streamline concept – and the focal point around which the field program was designed. Throughout the course of the CTMDP, the FMF interacted vigorously with the model developers by providing support in various ways. Early work provided direct support as an aid to planning the details and strategies of the field experiments and testing the limits of applicability of the dividing–streamline concept. Later work included exercises of "filling in the gaps" in the field data, furthering the understanding of the physical mechanisms important to plume impaction in complex terrain and in stably stratified flows in general, testing various modeling assumptions, providing data for "calibration" of various modeling parameters, and testing the ability of the laboratory models to simulate full–scale conditions. Simultaneously, the FMF responded to the needs of the regulatory arm of EPA, the Office of Air Quality Planning and Standards (OAQPS), by providing guidance concerning expected terrain effects and by conducting demonstration studies. Finally, several supplemental studies were conducted, broadening and expanding upon the specific requests of the model developers and the OAQPS.

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LIST OF SYMBOLS AND ABBREVIATIONS

Symbols

A	Terrain amplification factor, χ_{mx}/χ^{o}_{mx}
F	Froude number, U_∞/Nh
g	Acceleration due to gravity
h	Hill height
h_o	Height of density interface from surface
H_D	Dividing-streamline height
H_s	Source height
L	Length of ridge
N	Brunt-Väisälä frequency, $[-(g/\rho)d\rho/dz]$
U_∞	Towing speed or free-stream velocity
x_s	Source position in along-wind direction (origin at hill center)
y_s	Source position in crosswind direction (origin at hill center)
$\Delta\rho$	Density difference across interface
ρ	Fluid density
ρ_1	Density of fluid between interface and surface
σ_y	Standard deviation of crosswind plume width
σ_z	Standard deviation of vertical plume width
χ_{mx}	Maximum surface concentration
χ^{o}_{mx}	Maximum surface concentration in absence of hill

Abbreviations

ACCB	Axisymmetric (idealized) Cinder Cone Butte
CCB	Cinder Cone Butte
CTDM	Complex Terrain Dispersion Model
CTMDP	Complex Terrain Model Development Program
EPA	Environmental Protection Agency
ERT	Environmental Research and Technology, Inc.
FFT	Fast Fourier Transform
FMF	Fluid Modeling Facility
HBR	Hogback Ridge
OAQPS	Office of Air Quality Planning and Standards
TAF	Terrain Amplification Factor

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1. INTRODUCTION

In the late 1970's the Office of Air Quality Planning and Standards (OAQPS) of the Environmental Protection Agency (EPA) identified a crucial need to develop an improved mathematical model that dealt with plume impaction from large sources located in mountainous terrain under stable flow conditions. A workshop was convened (Hovind *et al.*, 1979) to focus on complex terrain modeling problems and to develop recommendations to EPA with respect to the design of a program of experiments and model development efforts. Subsequently, Holzworth (1980) outlined the EPA plan to achieve the objective through an integrated program of model development, fluid modeling experiments and field studies of plume–terrain interactions on hills of progressively increasing size and complexity. This multi–year, multi–faceted program is known as the Complex Terrain Model Development Program (CTMDP). The prime contractor for this effort is Environmental Research and Technology (ERT), which has produced a comprehensive series of annual reports, called Milestone Reports, that describe all phases of the research program. The specific references are: (1) Lavery *et al* (1982), (2) Strimaitis *et al* (1983), (3) Lavery *et al* (1983), (4) Strimaitis *et al* (1985), and (5) DiCristofaro *et al* (1986); a final report is to be completed in 1987.

The Fluid Modeling Facility (FMF) interacted vigorously with various groups participating in the CTMDP, and provided direct support and guidance in many different ways. Whereas the field work and model development effort up to the present time has been specifically focused on plume impaction under stable conditions, the work at the FMF has taken a much broader view. The FMF research program has ranged from the development of broad guidelines (*e.g.*, terrain amplification factors) and physical concepts (*e.g.*, dividing–streamline height) to modeling of specific sites (*e.g.*, Cinder Cone Butte) and regulatory applications (*e.g.*, good–engineering–practice stack height). The FMF has provided laboratory data to "fill in the gaps" in the field data (*e.g.*, measurements of plume deformations over hills) and tested the validity of convenient modeling assumptions (*e.g.*, cut–off hill approach).

This report summarizes the contributions, both direct and indirect, of the FMF to the CTMDP. The discussion provides a historical perspective and a comprehensive list of FMF's accomplishments with respect to furthering the physical understanding of flow and diffusion in complex terrain. In many cases the early research results were first published as internal documents or project reports or presented at workshops or conferences in order to speed the flow of information to the model developers. In most cases, these results have been published in peer-reviewed journals (which took, in one extreme case, 8 years to appear in print). For completeness and to provide the proper perspective, both references are cited at first mention in the text that follows; thereafter, only the journal publication is cited.

2. BACKGROUND

Research work conducted at the FMF prior to the inception of the CTMDP had a strong influence on the directions to be taken in the field work and on the type of model (*i.e.*, physical concepts) to be developed. The stratified towing tank was commissioned in 1976 (Thompson and Snyder, 1976) and rather fundamental studies were begun immediately on the structure of stably stratified flow over idealized three-dimensional hills and on diffusion from a point source within a stably stratified field of turbulence.

The first published reports on this work (Hunt *et al*, 1978; Hunt and Snyder, 1980) described the flow structure observed over a bell-shaped hill under neutral and stably stratified conditions. Earlier theoretical work by Drazin (1961), model experiments by Brighton (1978) and Riley *et al* (1976), and observations (*e.g.*, Queney *et al*, 1960) all indicated that, when the stratification is strong enough, the air flows in approximately horizontal planes around the topography. And this observation had been used by EPA in estimating the surface concentrations on hills caused by upwind sources of pollution (Burt and Slater, 1977). Up to that time, however, there had been little firm laboratory or field data as to how *strong* the stratification must be for any given streamline starting below the hill top to pass *round the side* rather than *over the top* of the hill. The Hunt and Snyder (1980) paper suggested a criterion for this change-over to occur on the basis of the low-Froude-number theory of Drazin (1961), and confirmed that criterion with experimental data.

The Drazin (1961) theory is applicable to strongly stratified flows around three-dimensional hills; indeed, it is asymptotically valid at zero-Froude-number. In simplistic terms, the theory suggests that the stratification inhibits vertical motions, so that fluid parcels are constrained to move in horizontal planes. Hence, the flow may be described in terms of two-dimensional flow around a cylinder which is not necessarily circular but, in fact, has the cross-sectional shape of the intersection of a horizontal plane with the three-dimensional hill. Hunt and Snyder (1980)

verified that, for a bell-shaped hill, a linearly stratified environment, and an effectively uniform approach-flow velocity profile, Drazin's theory was applicable in the range $F < 0.4$, where F is the Froude number ($= U_\infty/Nh$, U_∞ being the towing speed, N the Brunt-Väisälä frequency, and h the hill height).

More importantly, Hunt and Snyder (1980) showed evidence for a dividing streamline (on the centerplane determined by the flow and the axis of the axisymmetric hill) of height H_s such that streamlines below H_s would impinge on the hill surface and follow the surface around the sides, whereas streamlines above H_s would go over the top. They suggested the simple formula

$$H_s = h\,(1 - F) \tag{1}$$

as the criterion to determine whether a plume embedded in the flow approaching the hill would impact on the surface or surmount the top, for $0 < F < 1$.

Snyder *et al* (1980) presented further evidence from towing-tank experiments in support of the simple formula; they showed it was applicable to other shapes of axisymmetric hills, namely a cone and a hemisphere. Furthermore, they presented another simple formula and supporting experimental data for determining whether an elevated (step) inversion would surmount a hill. This second formula, which predicts the point at which the interface just reaches the hilltop, is

$$\frac{U_\infty^2}{(gh_o\Delta\rho/\rho_1)} = 2\left[\frac{h}{h_o} - 1\right], \tag{2}$$

where g is the acceleration due to gravity, h_o is the height of the interface (far upwind), $\Delta\rho$ is the density difference across the interface, and ρ_1 is the density of the fluid between the interface and the surface.

The Hunt and Snyder (1980) work also classified the types and causes of lee-wave patterns and separated flow regions on the lee side of this bell-shaped hill. Many measurements were made of surface flow patterns, separated regions, velocity profiles, impinging plumes, and streamline displacements over the hill. Hill-surface concentrations resulting from impinging plumes were measured simultaneously with the flow-structure measurements. Whereas the data were distributed to and used by numerous model developers and the information obtained therefrom was utilized for planning and model-development purposes, except for limited presentation at a 1979 symposium (Snyder *et al*, 1980), the bulk of the results did not actually appear in print until much later (Snyder and Hunt, 1984).

The implications of this flow structure with regard to plume impingement and resulting surface concentrations were amplified by Hunt *et al* (1979). This primarily theoretical work described two conceptual models for dealing with the problem of plume impingement. The first model was applicable to *strongly* stratified flow around three–dimensional hills, where vertical motion and vertical diffusion is negligible. The advective–diffusive equation around a three–dimensional hill which is axisymmetric about a vertical axis was solved (using an eddy diffusivity) to show how source positions on and off the centerline affect the trajectories and splitting of impinging plumes and the value and position of the maximum surface concentration on the hill. The results showed that the plume behavior is very sensitive to quite small changes in wind direction away from the direction that transports the plume onto a stagnation point, and the model provided a simple way to estimate the effect of these changes. This model also allowed the computation of concentrations within the separated, horizontally recirculating wake of the hill (source upwind of hill).

In the second model, a plume in a neutrally stable potential flow around a hemisphere was analyzed, also using the diffusion equation. The solutions showed how, because streamlines approach the surface of a three–dimensional hill much more closely than that of a two–dimensional hill, the maximum surface concentration on the hill *can* become very much greater than in the absence of the hill (but only for a limited range of source heights).

Prior to the inception of the CTMDP, another complex terrain model was developed by ERT under contract to EPA. The algorithm developed at that stage was generally applicable to plume behavior in stability conditions ranging from neutral to slightly stable. The general approach followed the theory of turbulent plumes embedded in potential flow fields as developed by Hunt and Mulhearn (1973), Snyder and Hunt (1984 – original manuscript made available to ERT in 1978), and Hunt *et al* (1979). This theory was applied to the calculation of ground–level concentrations using a Gaussian form of solution to the diffusion equation. Stream functions appropriate to the potential flow over a cylinder (aspect ratio, $h/L = 0$) and to the potential flow over a sphere ($h/L = 1$) form the cornerstones of the model. These solutions were extended to describe flows over terrain features of intermediate crosswind aspect ratio by a weighting of the two limiting stream functions. The derivation of this weighting scheme relied heavily on wind–tunnel experiments of flows over hills

of various aspect ratios (Snyder and Britter, 1987; data reports made available to ERT in 1979). Strictly speaking, this algorithm was applicable to neutral flows, but an empirical approximation was included to define streamline lowering caused by an imposed stable stratification. This empirical scheme was derived on the basis of the stratified towing-tank experiments of Hunt and Snyder (1980). Extensive comparisons of model predictions with FMF laboratory data were made for both neutral and weakly stable conditions. A full account of these model-development efforts and the essential physics of the model are provided by Bass *et al* (1981). These algorithms were subsequently incorporated into a routine operational model called COMPLEX/PFM (Potential Flow Model; Strimaitis *et al*, 1982). In COMPLEX/PFM, potential flow calculations are performed whenever the plume lies above the dividing-streamline height and the stability is between neutral and slightly stable; when the plume is below the dividing-streamline height, the model reverts to the standard COMPLEX I computation (see Wackter and Londergan, 1984). The COMPLEX I computation makes the level-plume assumption, with an effective doubling of surface concentration above the plume centerline concentration (Burt and Slater, 1977). This particular aspect of the complex terrain diffusion problem was one of the hotly contested issues that provided the impetus for the CTMDP.

A "strawman" was proposed by Holzworth and Snyder (1979) for discussion at the 1979 workshop convened by EPA to make recommendations with regard to the directions to be taken under the CTMDP. This strawman was hotly debated at the workshop and, in the end, was largely accepted by the workshop participants (Hovind *et al*, 1979). The plan that emerged (Holzworth, 1980) called for an enlargement of some of the major concepts arising from the previous work at the FMF, and for a verification of these concepts through the conduct of a series of field studies on hills of progressively increasing size and complexity.

Prior to the request for bids on the CTMD contract, a preliminary one-week field study of the nighttime flow patterns at Cinder Cone Butte was organized and conducted primarily by FMF personnel (Snyder *et al*, 1980); the primary purpose was to assess the suitability of Cinder Cone Butte as the site for the first small hill study (identified in the ERT Milestone reports as Small Hill Impaction Study # 1). Numerous observations were made of the flow structure and plume behavior around the hill, including (1) plumes spread

broadly in the lateral direction but very thinly in the vertical direction over the hill in neutral conditions, (2) lee-side separation under high-wind-speed, neutral conditions, (3) plume impingement under light wind, strongly stable approach flows, and (4) katabatic winds under light-wind, neutral approach flow conditions with clear night sky. Cinder Cone Butte was judged as ideally suited for the first small hill study in several respects. Finally, numerous suggestions were offered as an aid to the design and conduct of future field studies at this site (most of which were adopted in the later studies).

To recap the "state of the science" immediately prior to the contract award, the dividing-streamline concept had been shown to be a useful conceptual framework to use in describing the structure of strongly stratified flow around three-dimensional hills. It had only been shown to be valid, however, for quite a limited number of hill shapes, all of which were axisymmetric. It had only been verified under uniform stratification (linear density gradient) or under a step inversion (sharp density interface), under a uniform approach-flow velocity profile, and, of course, only under steady-state, small-scale laboratory conditions (although the preliminary field study provided reassurances of the validity of the concept).

3. DESCRIPTIONS OF EXPERIMENTS AND RESULTS

3.1 Direct Interactions with the Model Developers

The period 1980 through 1981

The major CTMDP contract was awarded in June, 1980, and the work plan called for the small hill impaction study to begin at Cinder Cone Butte (CCB) in September. Almost immediately, the FMF was called upon to conduct towing-tank experiments to aid in the detailed planning and design of the field experiments. The first request was to provide guidance with regard to the location of the main meteorological tower. The second request was to provide guidance for smoke- and tracer-release strategies, for preselecting locations for samplers and cameras, and for choosing in advance several different sampler strategies to account for variations in flow regimes and wind fields. The third request was to test the validity of an integral formula for predicting the dividing-streamline height.

At an early July meeting at ERT headquarters in Boston, MA, the question arose as to how to predict the dividing-streamline height when the wind profile was not uniform and the density gradient was not linear. This was of paramount importance in planning the release scenarios, as the release locations and heights were to be chosen in real time during the field study based upon the incoming real-time meteorological data. J.C.R. Hunt immediately sketched the now well-known integral formula as

$$\frac{1}{2}\rho U_\infty^2 (H_s) = g \int_{H_s}^{h} (h-z) \left[-\frac{\partial \rho}{\partial z}\right] dz \ . \qquad (3)$$

This formula had, in fact, been published 24 years earlier by Sheppard (1956) as a small note, actually in answer to his own question which arose at a meeting of the Royal Meteorological Society, although Sheppard's note was virtually unknown to the modeling community at that time. This integral formula is based upon simple energy arguments. Sheppard asked the question: "in a strongly stratified flow approaching a hill, does a particular fluid parcel at some height upstream possess sufficient kinetic energy to overcome

the potential energy required to lift itself through the potential density gradient from its upstream elevation to the hill top?" The left-hand side may be interpreted as the kinetic energy of the parcel far upstream at elevation H_s, and the right-hand side as the potential energy gained by the parcel in being lifted from the dividing-streamline height H_s to the hill top h through the density gradient $d\rho/dz$. This integral formula was presumably applicable to a fluid with any shape of stable density profile and, presumably, with any shape of approach-flow velocity profile. In practice, it must be solved iteratively, because the unknown H_s is the lower limit of integration; the formula can easily be reduced to the simpler formulae (1) and (2) by using the boundary conditions applicable to those special cases. The third request to the FMF was thus to verify this integral formula.

Three studies were conducted in the summer of 1980, and three reports were prepared in response to these requests. In the first study (Snyder, 1980a), twenty-six separate tows of a model of CCB were made through the tank in a two-week period. The objective was to assess the suitability of the particular site chosen for the main (150m) meteorological tower, *i.e*, was it close enough to CCB (≅100m high and 1km in diameter) to be representative of the flow approaching the hill, yet far enough away that the measurements were unaffected by the hill itself? It was impossible, of course, to meet both these criteria for all wind directions; the question addressed in the towing-tank studies, then, was whether the flow field at the proposed tower site would be perturbed by the hill, given the climatological ranges of prevailing wind directions for light, nighttime winds. Measurements were made of surface flow patterns, deformation of material lines (instantaneous crosswind releases of tracer), velocity profiles and streamline patterns over a model of CCB, and these measurements were compared favorably with predictions of potential flow theory. The findings from the study suggested that no significant perturbations to the approach wind field were to be expected due to the presence of the hill when the wind direction was within the range of the prevailing wind directions. In addition to the main tower, a shorter (20m) tower was recommended, to be erected at the trailer site (3km ESE of the hill). This recommendation was indeed implemented in the field study.

This was, in fact, the first real-terrain model (*i.e.*, non-idealized shape) to be studied in the FMF stratified towing tank. As a side benefit,

therefore, the study provided reassurances that the basic flow features and, of course, the same physical principles applied to more realistically shaped hills. Some examples are provided here to illustrate the point. Figure 1 shows an oblique view of the hill, where neutrally buoyant dye streamers were released from a horizontal rake upstream of the hill under strongly stratified conditions. The horizontal nature of the flow field is immediately obvious. Figure 2 shows a top or plan view of the CCB model under roughly similar conditions. One of the dye streamers obviously impinged on the upwind shoulder of CCB. Flow separation in the lee of the hill is dramatically illustrated in Figure 3, where vortex roll-up and eddy-shedding in the lee are quite vivid. The Kármán vortex street was a common occurrence at low Froude number; a street appeared to form at all elevations below the dividing-streamline height (at least for small Froude numbers), but the shedding frequency seemed to vary with elevation and motions at different elevations were seemingly uncorrelated with one another.

In the second phase of this summer series, eleven tows of the CCB model were made during which two of the model developers from ERT participated as observers. In this case, vertical rakes of tubes emitted neutrally buoyant dye at up to 6 elevations, with different colors of dye being emitted at the different levels. Each tow was filmed from the side using a camera that moved with the hill, and from directly below using a fixed camera pointed upward at the (inverted) model hill. The films were viewed with an analyst's projector, and the plume paths and envelopes were sketched. These results corroborated the previous results of Hunt and Snyder (1980) on idealized hills, *i.e.*, that plumes below the dividing-streamline height H_s and on a stagnation streamline would impinge on the upwind side of the butte and flow around the sides, and that plumes released just above H_s may produce maximum ground-level concentrations on the upwind side as they pass over the top. The results further emphasized that plumes travelling in a direction only slightly away from that of the stagnation streamline would tend to pass around CCB without significant impact, and that plumes released somewhat higher above H_s may be caught in strong downslope flows and produce maximum ground-level concentrations on the *lee* side of the hill. The results were also used, of course, for the originally intended purpose as a guide for planning of release and sampler strategies and selection of sampler and camera locations. The results are described by Bass (1980).

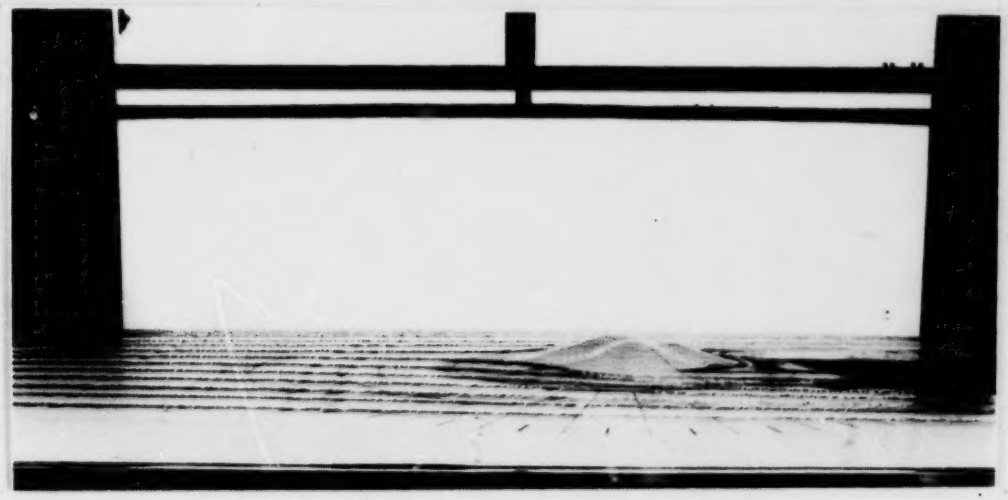

Figure 1. Oblique view of dye streamers released from a horizontal rake upwind of the CCB model at $z/h = 0.3$ under strongly stratified conditions ($F = 0.2$). Flow is from the left.

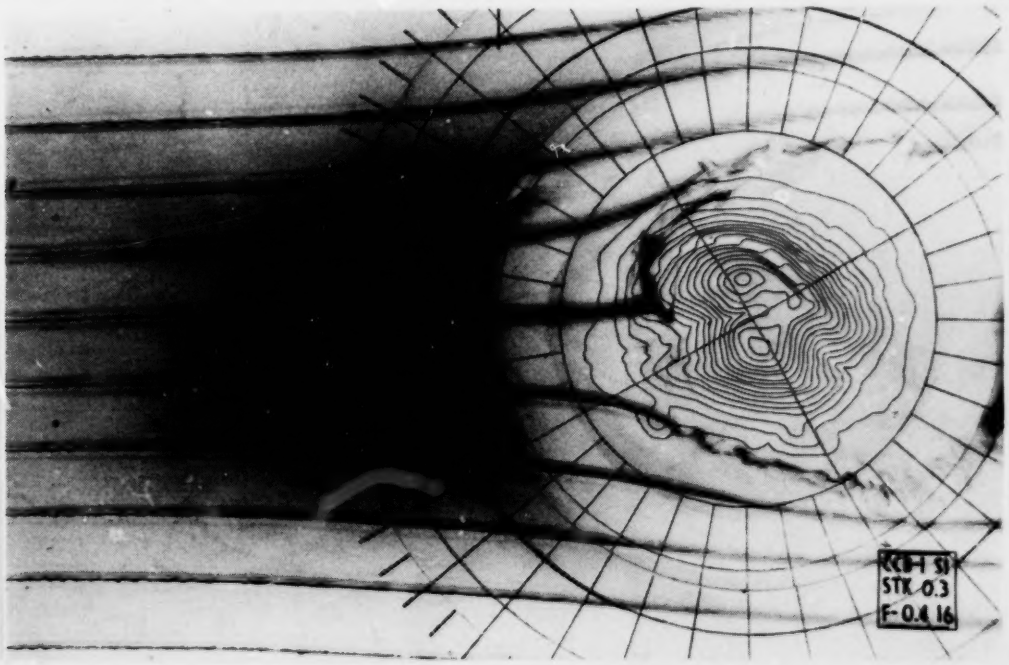

Figure 2. Top view of dye streamers impinging on CCB under strongly stratified conditions ($z/h = 0.3$, $F = 0.4$).

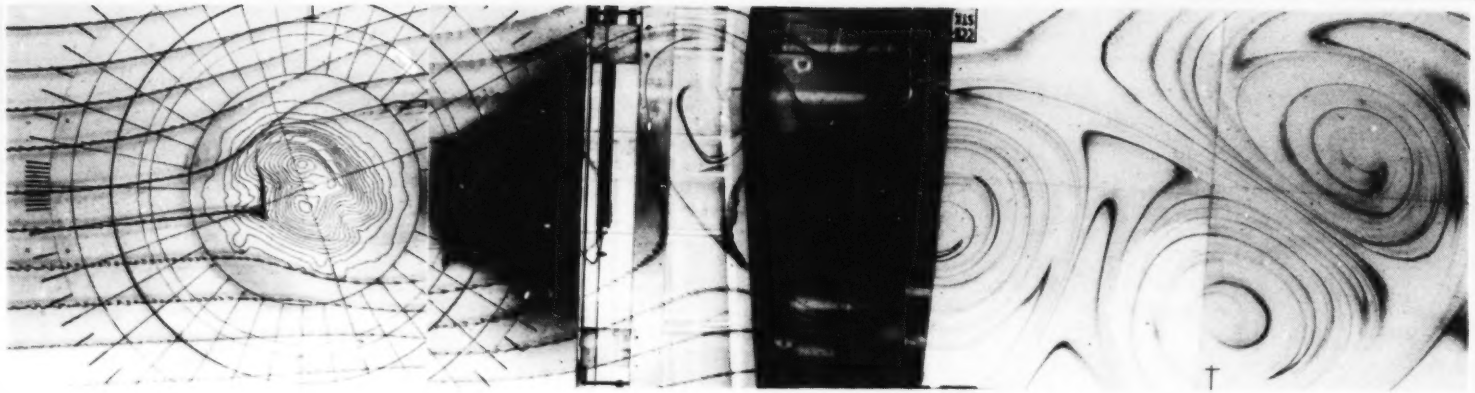

Figure 3. Top view of CCB under strongly stratified conditions showing vortex rollup and eddy-shedding in the lee ($z/h = 0.6$, $F = 0.2$). Unretouched sequential photographs cut and pieced together. Building roof shows in background of center portion.

In the third phase of this summer series, the goal was to test the validity of the integral formula for the height of the dividing streamline under density profiles similar to those expected at CCB. A typical nighttime temperature profile in the Snake River Basin (site of CCB) was found to consist of a strong, surface-based inversion of depth 50 to 100m and a weaker inversion above extending to several hill heights. Hence, the stratified towing tank was filled with a strong density gradient near the surface and a weaker gradient above. A vertical rake of 3 tubes was positioned well upwind of the hill, and neutrally buoyant dye was emitted from each tube. For each tow, a particular stack height (center tube) was chosen and the general formula was integrated numerically using the measured density profile to predict the towing speed required such that the center streamer would rise to the elevation of the saddle point of CCB, *i.e.,* the minimum height of the draw between the two peaks. If the formula were correct, then, the lower streamer should go around the side of the hill, the upper streamer should go over the top, and the center one should split. The height of the break-point between the two gradients was then reduced and the process repeated. In all, twelve tows were made, varying the height of the break-point or the dividing-streamline height (release height) each time.

Figure 4 shows a side view of the impinging streamers during a typical tow, *i.e.*, the upper streamer going through the draw, the lower streamer going round the side, and the middle one splitting. Figure 5 shows the results in quantitative fashion. The density profiles were integrated in accordance with Equation (3) to find the dividing-streamline heights (based on the height of the saddle point) as functions of the towing speed. These predictions are shown in Figure 5 as the continuous lines. The observations of the dividing-streamline heights made during the twelve tows are also plotted in the figure; the agreement between the predictions and observations is regarded as excellent. The error bars result because of some fluctuating behavior of the streamers, especially at the higher speeds; occasionally, an intermittent vortex at the top windward side of the hill would engulf all three streamers and they would all go round the sides temporarily; on other occasions, parts of the lower streamer could be observed passing through the draw. The results of this set of experiments (Snyder, 1980b) provided confidence in the validity of the general integral formula for predicting the height of the dividing streamline for a wide range of shapes of stable density profiles.

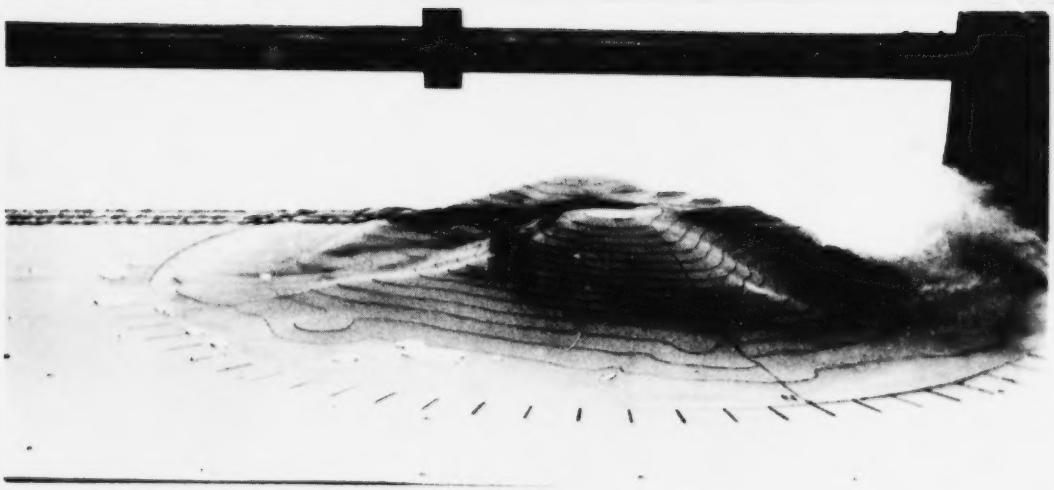

Figure 4. Oblique view of impinging streamers on CCB. Middle dye streamer is released at the dividing-streamline height; others at ±1cm (±6m full scale).

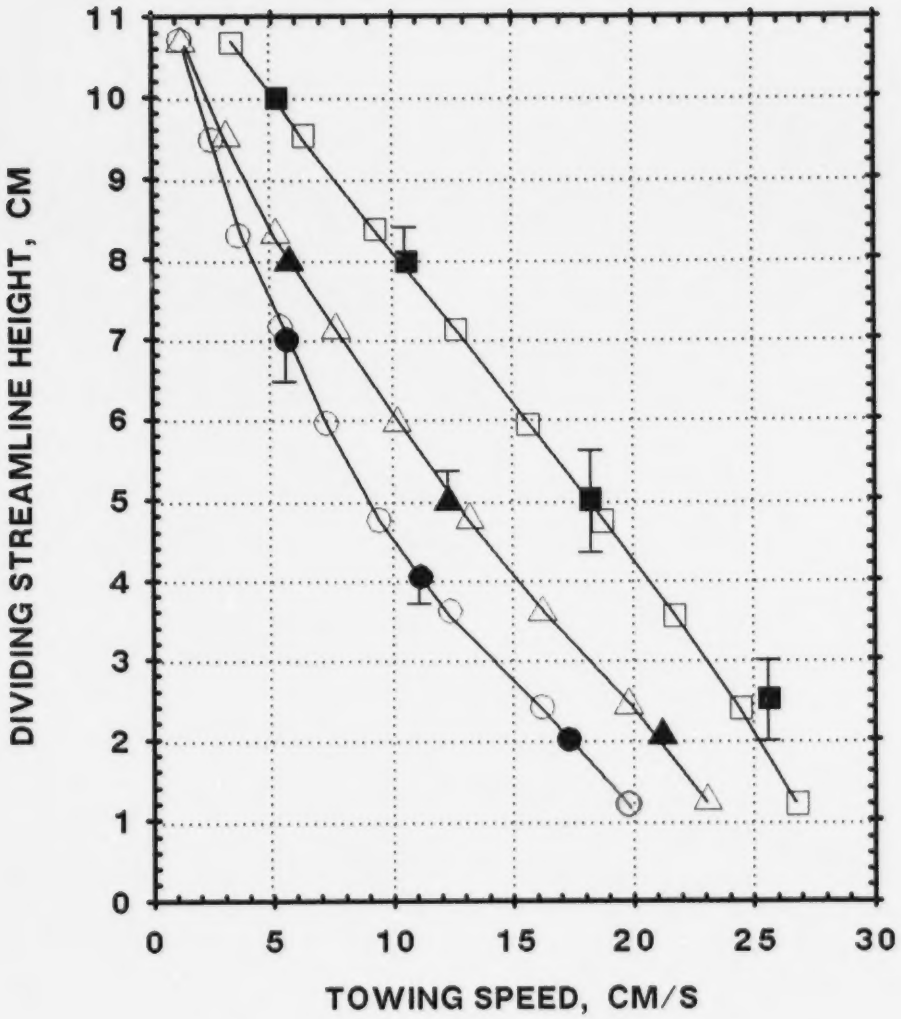

Figure 5. Comparison of predicted dividing-streamline heights with observations as functions of towing speed. Open symbols: predictions using integral formula; closed symbols: observations.

During the six-week field study at CCB, detailed measurements were made of wind, turbulence, and temperature profiles in the approach flow and at other positions on the hill. Sulfur hexafluoride (as a tracer) and smoke (for flow visualization) were released from a platform suspended from a mobile crane that allowed flexibility in positioning the source (height and location). One hundred samplers on the hill collected data on surface concentrations, and lidar was used to obtain plume trajectories and dimensions.

One particular hour from the field study was selected for simulation in the towing tank (Snyder and Lawson, 1981). That hour was 0500 to 0600, 24 October 1980 (Case 206), which may be characterized as very stable, *i.e.*, light winds and strong stable temperature gradients. Measurements made during the towing-tank experiments included ground-level concentrations under various stabilities and wind directions, vertical distributions of concentration at selected points, plume distributions in the absence of the hill, and visual observations of plume characteristics and trajectories.

This series of tows showed that the surface-concentration distributions were extremely sensitive to changes in wind direction. For example, Figure 6 shows that the distribution shifted from the north side of the hill to the south side with a shift of only 5° in wind direction. Comparisons of individual distributions with field results showed very much larger maximum surface concentrations and much narrower distributions in the model results. To account for the large variability in the winds measured during the hour, a matrix of 18 tows (three wind directions $\times$ six wind speeds) was conducted, and the concentration patterns were superimposed. A scatter plot of superimposed model concentrations versus field concentrations (Figure 7) shows a marked improvement over the single-tow comparisons. The largest model concentrations were within a factor of two of the highest field values, and 70% of the model concentrations were within a factor of two of the observed field values.

It was interesting to learn that, whereas the *location* of the maximum shifted dramatically with small shifts in wind direction, the *value* of the maximum changed very little with changes in wind direction or wind speed. Maximum surface concentrations approached those at the plume centerline in the absence of the hill during individual tows, but because of the extreme sensitivity of the location to wind direction, the plume was "smeared" broadly across the hill surface as the wind direction changed through only a few

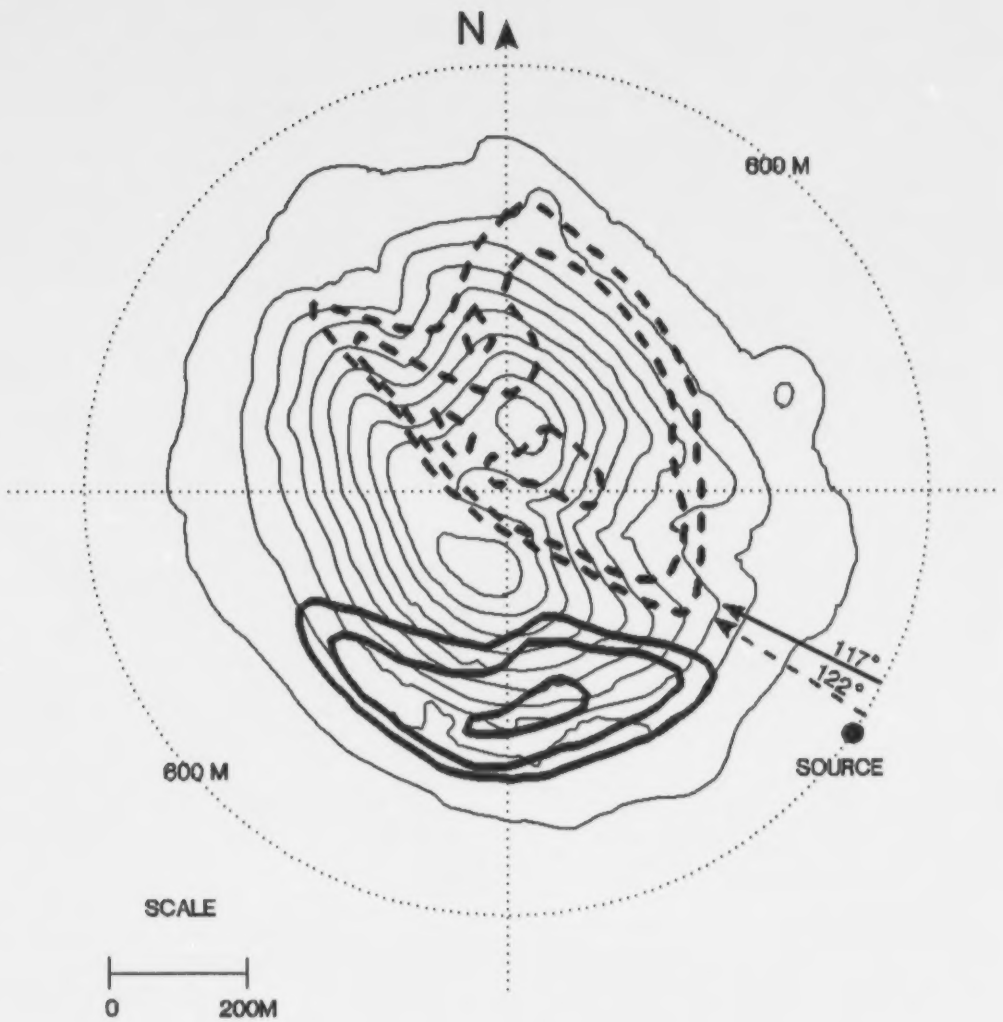

Figure 6. Concentration distributions measured during individual tows of CCB with $H_s/h = 0.31$ and $H_D/h = 0.38$; wind direction : ——— 117°, – – – 122°.

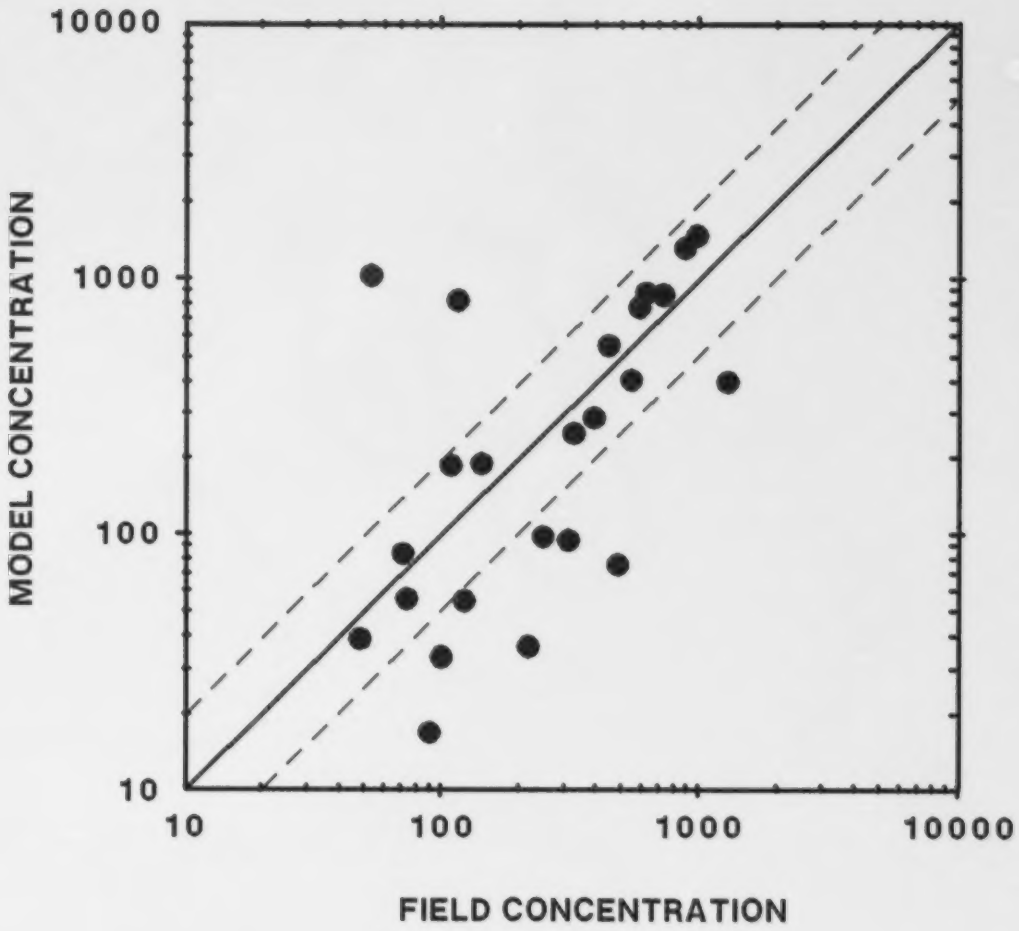

Figure 7. Scatter diagram comparing superposition of concentration distributions measured over Cinder Cone Butte with field distributions. Dotted lines denote factor of two on either side of perfect fit.

degrees. Therefore, short-term averages (≈5min) in the field may be expected to approach plume-centerline concentrations; longer-term averages (≈1h) may be expected to be reduced by factors of five to ten (or more depending upon the magnitudes of the fluctuations in wind speed and direction).

The period 1982 through 1983

Although considerable work had been done concerning the validity and limits of applicability of the dividing-streamline concept, several questions still remained. One question concerned the effects of shear in the approach-flow velocity profile. Another concerned the effects of the aspect ratio (ratio of crosswind length of the hill to its height) and, in particular, its applicability in strongly stable flows to a truly two-dimensional ridge. A third questioned the effects of the *slope* of the hill, and a fourth, the effect of wind angle on a long ridge.

A few earlier studies had shed light on some of these problems. Baines (1979), for example, had conducted towing-tank studies of low-Froude-number flows around a barrier with a gap. His results suggested

$$H_s/h = 1-2F \qquad (4)$$

for barriers with very small gaps, tending toward $H_s/h = 1-F$ (Equation 1) for those with wider gaps. Weil *et al* (1981) conducted similar towing-tank studies, extending the work of Baines, and found quite similar results. However, data from a field study by Rowe *et al* (1982) of stable air flow over a "long" ridge showed much better agreement with the data for axisymmetric hills (Equation 1) than for ridges with gaps (Equation 4).

In the early 1980's, a series of experiments was done by numerous investigators at the FMF and for a variety of different purposes. The overall objective was to gain fundamental understanding of flow and diffusion under stably stratified conditions in complex terrain, but the individual projects were designed with very specific and limited objectives in mind. Nevertheless, one aspect of each of the projects was to examine the concept of the dividing-streamline height, as it obviously had very important consequences with respect to the CTMDP. The results of most of these projects were published separately and independently, as will be referenced below, but the results concerning the validity and applicability of the dividing-streamline concept were extracted and published as an appendix (Snyder *et al*, 1983) to the Second Milestone Report (Strimaitis *et al*, 1983)

in order to provide timely support and guidance to (1) the mathematical modelers attempting to expand their models to include a wide variety of terrain shapes and approach flows and (2) planners of the Second Small Hill Impaction Study, which was to take place at the Hogback Ridge in northwestern New Mexico. This paper was subsequently published in a journal (Snyder *et al*, 1985). The individual laboratory experiments included:

1. Towing-tank studies on truncated, steep-sided ridges of various crosswind aspect ratios. These included examination of upstream "blockage" regions, surface flow patterns and lee-wave structure and were reported by Castro *et al* (1983); those aspects dealing specifically with the dividing-streamline concept were reported by Snyder *et al* (1983) and Snyder *et al* (1985).

2. Stratified wind-tunnel studies (in Japan) on *shear* flow over vertical fences of various crosswind aspect ratios and over a model of Cinder Cone Butte. (Snyder and Ogawa, 1982; Snyder *et al*, 1985).

3. Towing-tank studies on a truncated sinusoidal ridge with a maximum slope of 40° positioned perpendicular and at other angles to the approach wind direction (Lee *et al*, 1984a, 1984b).

4. Towing-tank studies on an "infinite" triangular ridge and a long sinusoidal ridge to test the validity of the "steady-state" assumption of flow upwind of an obstacle under strongly stratified conditions (Castro and Snyder, 1987c).

The conclusion from the studies with truncated triangular and sinusoidal ridges perpendicular to the wind was that the aspect ratio *per se*, does not have a significant influence on the dividing-streamline height H_s. Deviations from the $H_s/h = 1-F$ rule were attributed to the combination of shear in the approach flow and the very steep slope of the triangular ridges, which resulted in the formation of an upwind vortex with downward flow on the front faces of the ridges. The "1–*F*" rule was validated for the sinusoidal ridge with a length-to-height ratio greater than 16:1; in this case, the shear in the approach flow was much less pronounced, and the upwind slope was substantially smaller. Note that these deviations to the "1–*F*" rule did not invalidate Sheppard's concept, but required a reinterpretation of the rule as a necessary but not sufficient condition, *i.e.*, a fluid parcel may possess sufficient kinetic energy to surmount a hill, but it does not necessarily do so.

In the stratified wind-tunnel studies, reasonably strong shear layers with depths more than twice the hill heights were developed in conjunction with strong stable temperature gradients. These approach flows provided dividing-streamline heights as large as $0.75h$. In the vertical fence studies with a stratified approach flow, the shear was found to have an overwhelming influence. The conclusions were: (a) as in the triangular ridge studies, the aspect ratio was relatively unimportant; the basic flow structure was independent of aspect ratio; (b) the shear, in conjunction with the steep slope, created an upwind vortex such that plumes were downwashed on the front faces; and (c) under strong enough stratification, there was a limit to the downward penetration of elevated streamlines; the extent of this penetration appeared to be predictable as a balance between kinetic and potential energies. However, when these same shear flows approached the much lower sloped CCB model, there was *no* evidence of upwind vortex formation. Limited concentration measurements on the CCB model suggested that Sheppard's integral formula correctly predicted the height of the dividing streamline.

From the sinusoidal ridge studies with wind angles at other than 90°, it was concluded that the effect of deviations in wind direction (from 90°) are relatively insignificant until the wind direction is in the vicinity of 45° to the ridge axis. At 30°, significant departures from the "1–F" rule were observed; the fluid had sufficient kinetic energy to surmount the ridge, but found a path requiring less potential energy round the end of the ridge. When the dye streamers were moved closer to the upstream stagnation streamline (upwind of the upstream end of the ridge), they behaved according to the "1–F" rule.

The two-dimensional ridge studies showed that steady-state conditions are not established in strongly stratified flows (say $F < 1$). Two different physical mechanisms give rise to this unsteadiness; one is called "squashing", the other, upstream wave propagation. Brief explanations will be given here; the interested reader should consult the cited references.

The squashing phenomenon is most easily described in terms of the simple energy arguments as used in deriving Sheppard's formula (Equation 3). As discussed there, a fluid parcel with insufficient kinetic energy to overcome the potential energy requirement to surmount the hill must pass round the sides of the hill. But a two-dimensional hill has no sides around which to pass (in a towing-tank, a "two-dimensional" hill is one that spans the entire

width of the tank). Hence, the fluid parcel must be brought to rest. In the towing tank, since the fluid is generally at rest and the hill is towed, this means that the fluid ahead (upstream) of the hill must be pushed ahead of the hill, instead of being allowed to surmount the hill top. However, the upstream endwall of the towing tank, of course, prohibits this fluid from being pushed. Hence, the fluid between the hill and the upstream endwall is "squashed" as the hill approaches the endwall; because the fluid is incompressible, it must rise and spill over the top of the hill, just as the water in a bucket will rise and spill over the top when the sides are "squashed".

This squashing phenomenon seems to have no counterpart in the atmosphere. If true blocking occurred upwind of an "infinite" ridge in the atmosphere, it seems that the flow would be blocked to infinity upwind (*i.e.*, there is no "endwall" forcing the flow toward the ridge). In more practical terms, "blocking" upstream of a very long ridge would imply "upstream influence" to very large distances, possibly through an upstream-propagating front, which would imply non-steady-state behavior. From another viewpoint, there are no infinite ridges in the real world, so that fluid parcels can always be diverted around the obstacles without changing their elevation.

The results leading to the "1-2F^2" formula (Equation 4) by Baines (1979) and Weil *et al* (1981) for two-dimensional ridges and ridges with gaps were surprising because they suggested that fluid parcels could surmount the hills even though they had insufficient kinetic energy to do so. Snyder *et al* (1983, 1985) suggested that these earlier results were erroneous; that they were largely due to the squashing phenomenon, *i.e.*, the gaps in their ridges were insufficiently large to allow a "relief valve" to avoid the squashing.

Upstream *wave* propagation is also possible in stratified flows. The introduction of an obstacle in a stratified flow on which lee waves can form will result in "columnar" disturbances extending upstream (see Turner, 1973); if such motions are present, they will modify the approaching flow. These columnar disturbances take a sinusoidal form in the vertical, with the "mode" (number of oscillations) being dependent upon the Froude number based on the depth of the tank. An example of an upstream columnar disturbance is shown in Figure 8. Dye crystals were dropped into the stratified tank at a position 16m upstream of the starting position of an obstacle (in this case, a vertical fence) which was to be towed along the water surface. These crystals

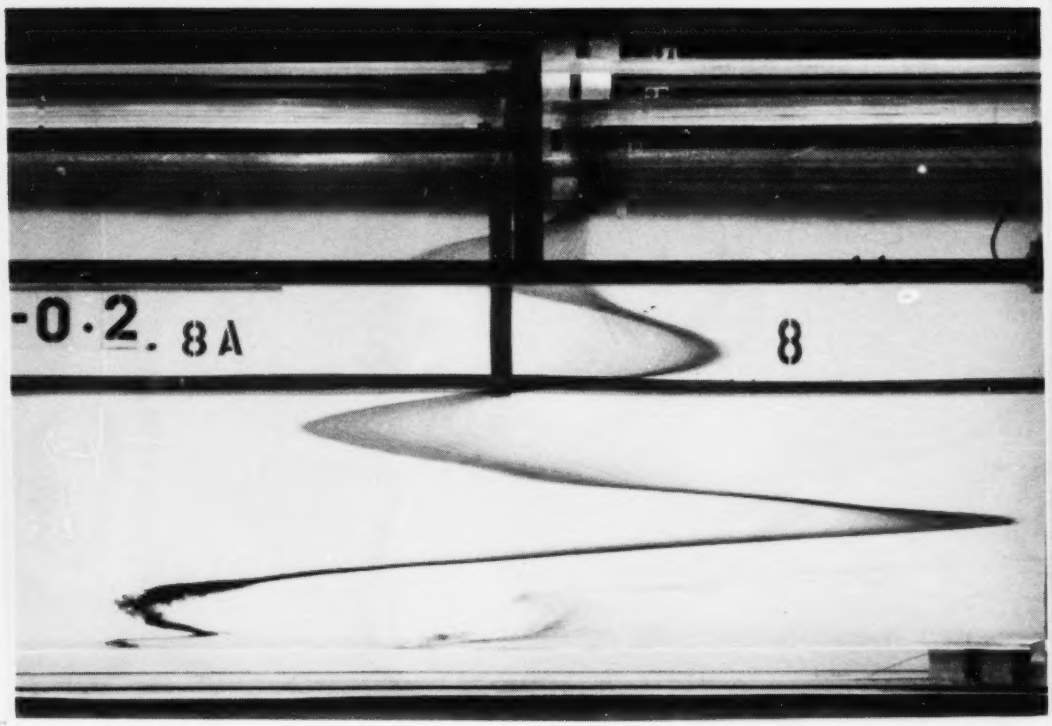

Figure 8. Deformation of vertical dye line by upstream columnar disturbances. Dye line was formed at a location 16m upstream of starting position of fence, at time when fence was at $x = 12.5$m (18.6h upstream of fence). Photograph was taken when fence was at $x = 13.8$m (11.6h upstream of fence). Fence is out of photograph, approaching from top left.

dissolved as they sank to the bottom, leaving behind a vertical dye line. The dye line was formed after the commencement of the tow, and the photograph was taken well before the obstacle reached the dye-line position, *i.e.*, the dye line was deformed by the upstream columnar disturbance into the sinuous curve shown in Figure 8.

These columnar disturbances, unlike the squashing phenomenon, do have counterparts in the real atmosphere. They result in "blocking" and "upstream influence". However, in the laboratory tank, these upstream waves are reflected from the upstream endwall of the tank and return to modify the flow locally around the model hill; this reflection from the upstream endwall does *not* have a counterpart in the real atmosphere. Baines (1979) argued that valid observations could be made of the flow over and around the obstacle in isolation (in the absence of end effects) by making the observations after steady state was reached (estimated by direct observation), but before reflected upstream motions arrived. Evidently, he believed that a *local* steady state was achieved in that, at some not-too-distant point upstream of the obstacle, steady-state velocity and density profiles were established before the reflected motions returned to modify them.

Snyder *et al* (1983; 1985) showed that steady-state conditions are not established in strongly stratified flows (say $F<1$) over two-dimensional ridges. The squashing phenomenon and reflections of upstream columnar disturbances continuously changed the shapes of the "approach flow" velocity and density profiles. Thus, these experiments have no analogue in the real atmosphere. Further, because long ridges cut by periodic small gaps require very long tow distances in order for steady state to be established, Snyder *et al* concluded that the previous laboratory studies were not valid models of atmospheric flows; specifically, the $H_s/h = 1-2F$ formula proposed for flow about ridges with small gaps is not expected to apply to the real atmosphere.

Further work was done to better understand the nature and causes of these upstream motions and lee waves by Thompson and Snyder (1984), Castro (1987) and Castro and Snyder (1987b, 1987c), but the interpretation of these results is somewhat controversial. More work is required to establish the precise relationships between model size and shape, stability, and tank size, shape and configuration in order to determine the limits of applicability of fluid modeling and ranges of transferability to the atmosphere.

The second Small Hill Impaction Study was conducted during October 1982 at Hogback Ridge (HBR) (≅100m high) near Farmington, NM. In providing input to the experimental design, the FMF conducted a series of wind-tunnel and towing-tank flow-visualization experiments prior to the field study. The laboratory studies were designed to investigate

- plume height above the surface over the hill crest and at the upwind edge of the hill,
- apparent size of any plume deformation upwind of the hill,
- lee wave importance and structure, and
- sensitivity of the plume trajectory to "wind angle".

This information was subsequently used by the field designers to guide the design of the smoke and tracer-gas release protocols at HBR, and to help select sampler and camera locations.

Two tests were made in the wind tunnel. One test was done with the ridge perpendicular to the flow, the other with the ridge rotated by 30°. These tests suggested that in neutral conditions the streamline patterns were similar to those expected from potential flow theory; a plume released at a given height upwind of the ridge should traverse the crest at an elevation of one-half its initial height. The test with the ridge at an angle to the flow showed only a very small ($<4^{\circ}$) deflection of the plume path as the plume traversed the ridge.

Eight individual tows of the HBR model were done in the stratified towing tank, varying the Froude number and wind direction, and each time releasing dye at eleven different elevations upstream. Heights of these dye streamers were measured at the upstream base and at the crest of the ridge. These experiments showed that, during weakly stratified conditions, plumes rose near the upwind base and fell over the crest to near or slightly lower than their upstream heights. Low-level releases experienced extensive mixing. More detailed results are contained in the Third Milestone Report (Lavery *et al*, 1983, p. 117-123).

Around this same time period, the FMF undertook two separate laboratory experiments that attempted to simulate two specific one-hour periods as observed in the field at Cinder Cone Butte. The first simulated a neutral stability period in the Meteorological Wind Tunnel (Thompson *et al*, 1983).

The second simulated a moderately stable period in the stratified towing tank (Eskridge *et al*, 1983). [Recall that the simulation of a strongly stable period was described earlier (Snyder and Lawson, 1981).]

In the summer of 1983, Ben Greene and colleagues from ERT, in cooperation with the FMF staff, conducted experiments in the Meteorological Wind Tunnel to characterize the response of the Climatronics UVW propeller anemometers. The primary objectives of the experiments were to determine the calibration curves and the non-cosine response corrections, especially at low wind speeds. The results of these tests are contained in the Fourth Milestone Report (Strimaitis *et al*, 1985, p. 85-93). The calibration factors and non-cosine response correction factors were applied to the HBR data base in forming the Modeler's Data Archive.

In late summer of 1983, discussions were held with ERT concerning possible contributions of FMF to the Full-Scale Plume Study planned for the following year at the Tracy Power Plant near Reno, NV. Considerations of scaling the site for towing-tank studies revealed that, at any reasonable scale, the model would appear as a two-dimensional ridge with a small gap (river valley) running through it. Recent work at the FMF as discussed above had shown that this situation could not be modeled under strongly stable conditions. Hence, specific site modeling at the Tracy Power Plant was not undertaken at the FMF. Instead, other studies in direct support of the model-development effort were undertaken as described below.

The period 1984 through 1985

In September 1983, A. Venkatram, D. Strimaitis and R. Britter from ERT requested that the FMF conduct two studies in support of their model-development efforts. The first study attempted to shed light on the question of the validity of the assumption of a *flat* dividing-streamline surface, a key assumption in the model under development. The second study was to provide a complete set of data on neutral flow and diffusion around a three-dimensional hill with a shape and slope approximating that of Cinder Cone Butte. These data were to help ERT to evaluate the separate effects of plume deformation kinematics and those of increased turbulence around the hill.

The first study, testing the validity of the flat dividing-streamline assumption, consisted of a series of 26 tows of a model hill in the stratified

towing tank. The model hill was the fourth–order polynomial (45° maximum slope) used by Hunt *et al* (1978), except that it was in this case instrumented with 100 sampling ports located along 8 radial lines. The density gradient was linear and the dividing–streamline height was fixed at half the hill height. Effluent was released at three elevations above the dividing–streamline height. *Pairs* of tows were made such that, in one tow, the hill (upside down) was fully immersed in the water and the towing speed was adjusted to provide a "natural" dividing–streamline surface. In the second tow of the pair, the model (baseplate, hill, and source, as a unit) was raised out of the water to the point where only the top half of the hill was immersed, thus, forcing a *flat* dividing–streamline surface, while all other conditions remained identical. Concentration distributions were measured on the hill surface (and in the absence of the hill). Concentration distributions from each pair of tows were compared to ascertain any differences between the "natural" dividing–streamline surface and the (forced) flat dividing–streamline surface. A comparison of surface–concentration patterns from a typical pair of tows is shown in Figure 9, and a scatter plot comparing concentrations on a port by port basis is shown in Figure 10. These results showed that the assumption of a flat dividing–streamline surface is a reasonable assumption to make, at least with regard to predicting the locations and values of the maximum surface concentrations and areas of coverage on the windward side of the hill. The results are contained in an appendix to the Fourth Milestone Report (Snyder and Lawson, 1985a) and were presented at the Third International Symposium on Stratified Flows (Snyder and Lawson, 1987).

The second study, providing a relatively complete set of data on flow and diffusion around a three–dimensional hill, was conducted in the Meteorological Wind Tunnel. The primary objective was to determine the influence of the hill on the maximum ground–level concentration (glc) and to locate the source positions where this influence was greatest. All measurements were made with an approach flow that simulated the neutral atmospheric boundary layer measured at Cinder Cone Butte. However, the nearly axisymmetric CCB shape was replaced by a truly axisymmetric hill represented by a simple mathematical formula, and having a maximum slope of 24° (the same as CCB).

The measure of the hill's influence on the maximum glc was the "terrain amplification factor" *A*. This factor is defined as the ratio of the maximum

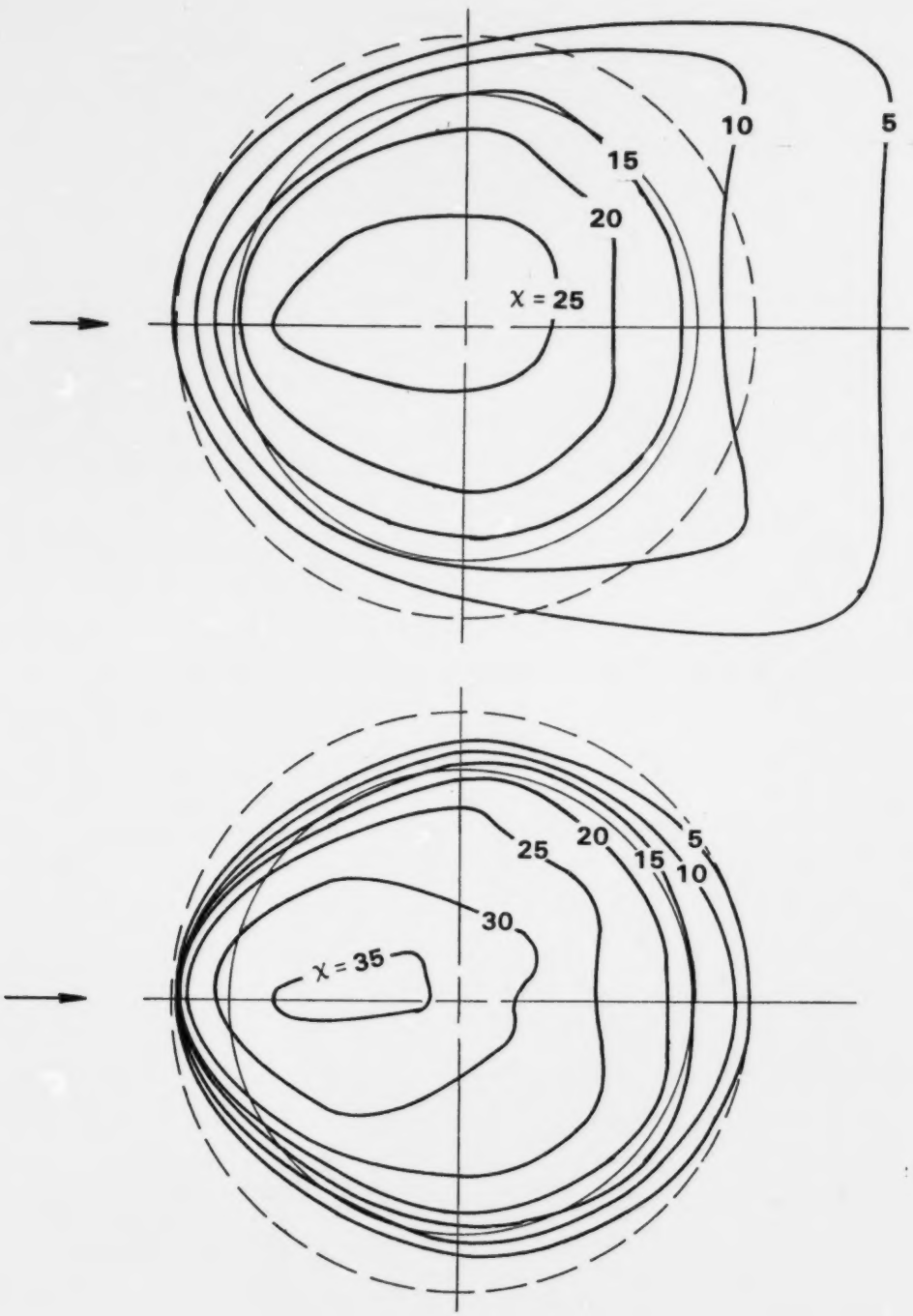

Figure 9. Concentration distributions measured on the hill surface with $H_D/h = 0.5$ and $H_s/h = 0.6$. Top: fully submerged; bottom: half submerged. Dotted circle indicates half the hill height.

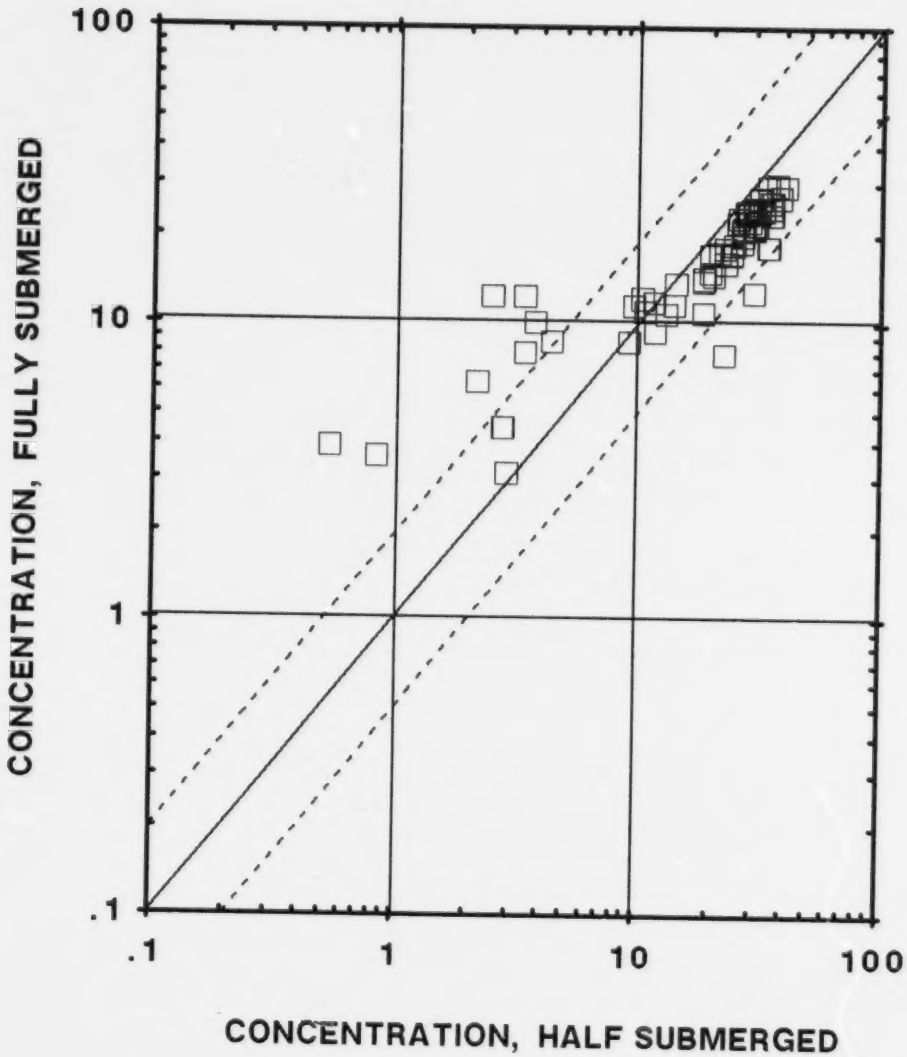

Figure 10. Scatter plot comparing concentrations on fully immersed hill with those on half-immersed hill on a port by port basis. $H_s/h = 0.6$, $H_D/h = 0.5$.

glc observed in the presence of the hill to the maximum observed in the absence of the hill. The locations of the maxima are not considered in this evaluation; the maxima may be found at entirely different places in the presence and in the absence of the hill.

A matrix of source locations was used covering the range from 4 to 16 hill heights (h) upstream of the hill center and to 1.25h in the vertical. A map of terrain amplification factors is shown in Figure 11. The presence of the hill was found to influence the transport and dispersion of the plume and to increase the maximum glc in three ways. For low sources at moderate distances from the hill, the reduction in mean wind speed and increase in turbulence allow the plume to reach the ground surface closer to the source, thus producing higher concentrations than in the absence of the hill. Plumes from higher sources may be thought of as being intercepted by the hill, that is, the hill penetrates the plume to where the concentrations are greater than those that would occur at ground-level farther downstream over flat terrain. For yet higher sources, the streamline convergence over the hill top and the corresponding downward flow and much enhanced turbulence in the lee of the hill again bring the plume to the ground more rapidly than over flat terrain. Terrain amplification factors ranged from near 1.0 to 3.63, and the range of source locations that produced an amplification factor greater than 1.4 extended to an upwind distance of 14 hill heights. These results were reported in an appendix to the Fourth Milestone Report (Thompson and Snyder, 1985b).

In the fall of 1984, ERT requested a list of data sets available from previous complex terrain studies that had been conducted at the FMF. A report was prepared by Thompson *et al* (1985) listing 24 separate complex terrain studies. Each project was synopsized with a brief description of the project, the name of the principal investigator(s), the facilities used, types of data collected, names of data reports available, major conclusions reached, listing of published results from the project, and a listing and description of the data files available.

An earlier request (prior to summer 1983) from the modelers at ERT had been to provide data on streamline trajectories in neutral and stratified flow over a three-dimensional hill, *i.e.*, to provide data to use in developing algorithms for predicting lateral and vertical streamline displacements over a hill as functions of source location and stratification. Earlier work on this

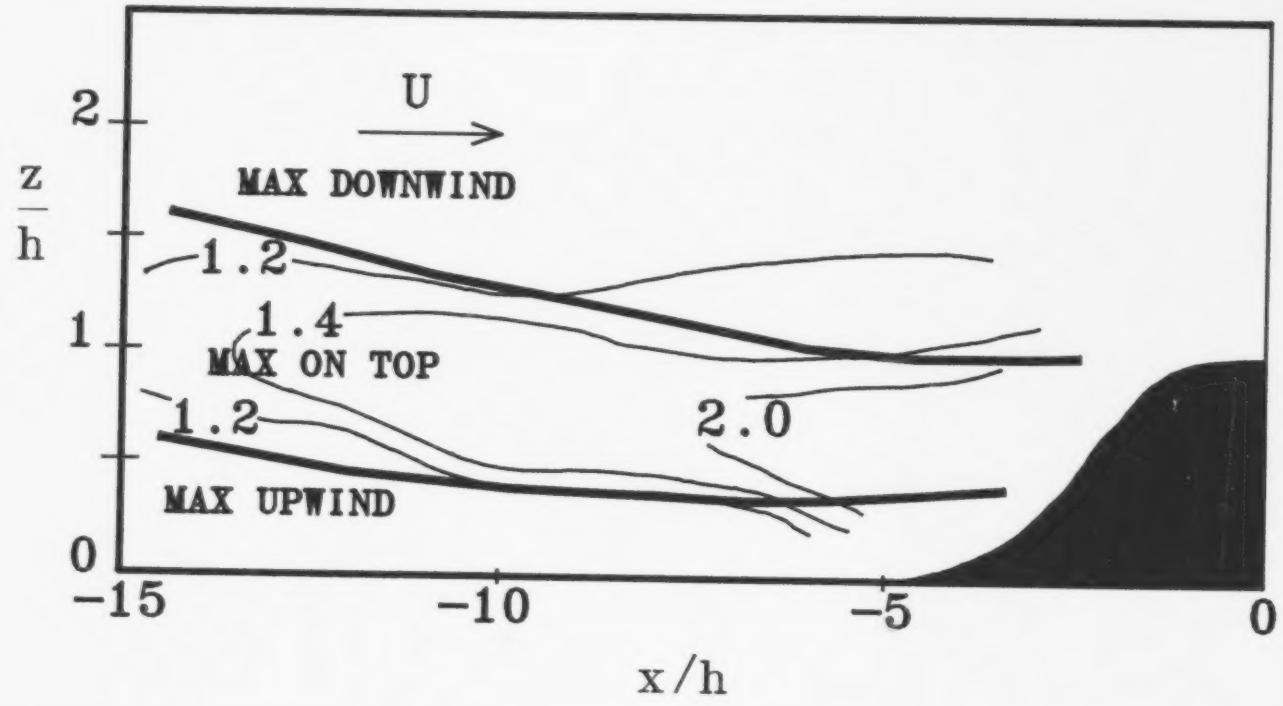

Figure 11. Terrain amplification factors measured upwind of axisymmetric CCB model. Heavy lines divide the region into areas where the source position produced the maximum glc upwind of the hilltop, between the hilltop and the separation point, and downwind of the hill. Note that the vertical scale is exaggerated by a factor of 3.

project had been set aside because of experimental difficulties and because of the more urgent requests described immediately above. Having completed those studies, work commenced again on the streamline trajectories.

In attempting to predict the maximum glc from a source upwind of a hill, the most important feature of the flow is the displacement of the mean streamline through the source, because that displacement determines how near to the surface the "centerline" of the plume will reach. The exact path taken by the plume in circumventing the hill and the plume's closeness of approach to the hill surface are critical in determining the location and magnitude of the glc's. These displacements are known to be strongly affected by the hill shape and especially by the stratification in the approach flow. The purpose of this study was thus to characterize the effects of stability on the horizontal and vertical deflections around an isolated hill. A large set of streamline trajectories over the axisymmetric CCB model was measured using the stratified towing tank. Three-dimensional coordinates of the streamlines (86 independent trajectories) were determined through stereographic analysis of photographs of dye streak lines released at a matrix of source positions (heights and lateral offsets from the hill/flow centerline), and at stabilities ranging from strongly stable to neutral (Froude numbers of 0.6, 1.0, 2.0, and ∞). These measurements provided a relatively complete data set for testing mathematical models and algorithms of the detailed structure of stratified flow over hills. The results were presented in an appendix to the Fifth Milestone Report (Snyder *et al*, 1986).

As an example use of the data set, a mathematical model using linear theory and a Fast Fourier Transform (FFT) technique to predict these streamline trajectories was evaluated and described in the above appendix by Snyder *et al* (1986) and, with some additional work and computations, by Thompson and Shipman (1986). The calculated results agreed well with the experimental results for neutral flow. In the stable flow ($Fr = 2.0$), however, lateral deflections were underpredicted and vertical deflections were overpredicted using the FFT model.

The period 1986 through present

In February 1986, ERT conducted a Complex Terrain Workshop at Research Triangle Park, NC (Lavery *et al*, 1986). Each participant was beforehand provided a diskette containing the Complex Terrain Dispersion Model (CTDM)

code and a draft User's Guide and was asked to exercise the model to assess its overall effectiveness and validity in whatever way he chose. The purpose of the workshop, then, was to exchange information on the results of these exercises and to make recommendations to the model developers concerning further refinements of the CTDM model.

The present author exercised the CTDM by comparing is predictions with previous laboratory measurements of flow and diffusion over hills made in the FMF. This was accomplished in four phases. In phase 1, CTDM calculations were compared with wind-tunnel simulations of plumes released upwind of two- and three-dimensional hills in a neutral atmospheric boundary layer. Terrain amplification factors were compared for a matrix of source locations upwind of the hills. This phase was intended to test the LIFT module of CTDM, where the stratification was neutral and the potential flow calculations of LIFT should be most applicable. In phase 2, CTDM calculations were compared with stably stratified towing-tank observations, where plumes were released above the dividing-streamline height upwind of a three-dimensional hill. This phase was intended to again test the LIFT module, but this time under strongly stratified conditions. In phase 3, CTDM calculations were compared with strongly stratified towing-tank observations wherein plumes were released below the dividing-streamline height upwind of the Cinder Cone Butte model. This phase was intended to test the WRAP module exclusively. In phase 4, CTDM calculations were made for one selected hour of field conditions, and were compared with results of towing-tank observations. This phase was intended to exercise both the LIFT and WRAP modules of CTDM.

The results, made available in a detailed report that was distributed to the workshop participants (Snyder, 1986), may be summarized as follows:

1. From the neutral flow simulations (phase 1), the hill effects (as exemplified through computations of terrain amplification factors) appeared to be much too small. Reasons speculated for this discrepancy included: (a) plume trajectories were too far from the hill surface, (b) potential flow calculations did not properly handle the deep boundary-layer flow approaching the hill, or, more likely (c) the plume centerline did approach the hill surface closely enough, but the plume did not mix to the the surface through the hill-surface boundary layer.

2. From the stable flow simulations with releases above the dividing-streamline height (phase 2), it appeared that the plume trajectories were again too far from the hill surface. Vertical deflections of streamlines appeared to be strongly overestimated and lateral deflections appeared to be strongly underestimated. In the

towing tank, plumes released slightly above the dividing-streamline height spread broadly but thinly to cover the entire hill surface above the dividing-streamline height, whereas the CTDM plume was apparently deformed only slightly – it "hung together" in going over the top of the hill. An apparent shortcoming of LIFT at that time was its lack of appropriate treatment of the stratification effects in the flow that surmounted the hill, *i.e.*, streamline (hence, plume) deformations under quite strongly stratified flows (Fr≅1) were treated the same as those for neutral flow (Fr=∞).

3. From the stable flow simulations with releases below the dividing-streamline height (phase 3), the WRAP module yielded rather poor results except when the input parameters (primarily σ_v) were within a fairly closely restricted range. WRAP could not handle narrow plumes.

4. From the Case 206 simulations (phase 4), CTDM appeared to do a reasonable job of predicting the values of the highest concentrations. Improvements in predictions from the 12/5-minute mode over the 1-hour mode appeared to be small, at least in terms of calculating the highest concentrations, and did not appear to be justified on the basis of the additional computation costs.

Also at the CTDM Workshop, the participants were divided into three workgroups to discuss and make recommendations concerning (a) algorithms, (b) evaluations and (c) applications. One outcome of the Algorithm Workgroup was the postulate of a hill-surface boundary layer that would result in rapid mixing of plume material to the hill surface [a possible mechanism, lacking from CTDM, that could have resulted in the rather poor agreement between the neutral wind-tunnel results (discussed above) and the predictions of CTDM]. Further discussions of the workgroup indicated the need for a "definitive" data set on plume deformations over a realistic hill shape, for appropriate adjustment or "calibration" of the T-factors (terrain correction factors) in CTDM. Hence, the FMF agreed to conduct further studies with the following goals:

1. Investigate the existence and/or effects of a "hill-surface boundary layer" that might result in rapid mixing of material from an elevated plume onto a hill surface.

2. Provide detailed plume-structure data over a realistic hill shape, *i.e.*, horizontal and vertical plume deflections and deformations over a hill.

To satisfy the first goal, two interchangeable axisymmetric (idealized) Cinder Cone Butte (ACCB) models were constructed. One of the models had a smooth surface; the other was covered with gravel. Effluent was released from

an upstream source with height such as to obtain a plume that just "grazed" the hill top. The postulate here was that the roughness on the surface would maximize the effects of a rapid-mixing layer near the hill surface, thus mixing material from this elevated plume to the surface, whereas the smooth surface would minimize the effects of this mixing layer. The results showed that the postulate of an "inner hill-surface boundary layer" was untenable; extremely steep concentration gradients remained near the hill surface, even when the hill was roughened, so that rapid mixing was not induced by the hill-surface boundary layer.

To satisfy the second goal, a series of measurements was made of plume characteristics in flat terrain and over a three-dimensional hill. Effluent was released at a number of elevations, upwind distances, and positions laterally offset from the centerplane determined by the wind direction and the center of the hill. Sufficient concentration measurements were made to enable the construction of plume cross sections at the downwind position of the hill center and, in a few cases, at the upwind base of the hill. These data were analyzed to provide the desired information on horizontal and vertical plume deflections and deformations effected by the hill. One of the more dramatic examples is shown in Figure 12. In this case, the source was on the centerplane at ground level, 6 hill heights upwind of the hill center (the skirt of the hill extended to 5h). Plume cross sections measured at the position of the center of the hill, both in the presence and in the absence of the hill, are shown. The hill effected a 91% increase in the lateral plume width. In this case, the maximum surface concentration (at the same downwind distance) was decreased by a factor of 2 but, of course, the area of coverage by large concentrations was greatly increased. Detailed data reports were provided to ERT in March 1986, and the results were published by Snyder and Lawson (1986).

Subsequent to the CTMD Workshop (and as a result of the rather poor comparisons of the CTDM predictions of terrain amplification factors with wind-tunnel data), refinements were made to CTDM. Specifically, the strain inferred or measured over the crests of two- and three-dimensional hills in the wind tunnel were used in the calculations, *i.e.*, the T-factors in the model were adjusted in accordance with wind-tunnel data. Substantial improvements in the CTDM predictions of terrain amplification factors were obtained, as described by Strimaitis and Snyder (1986).

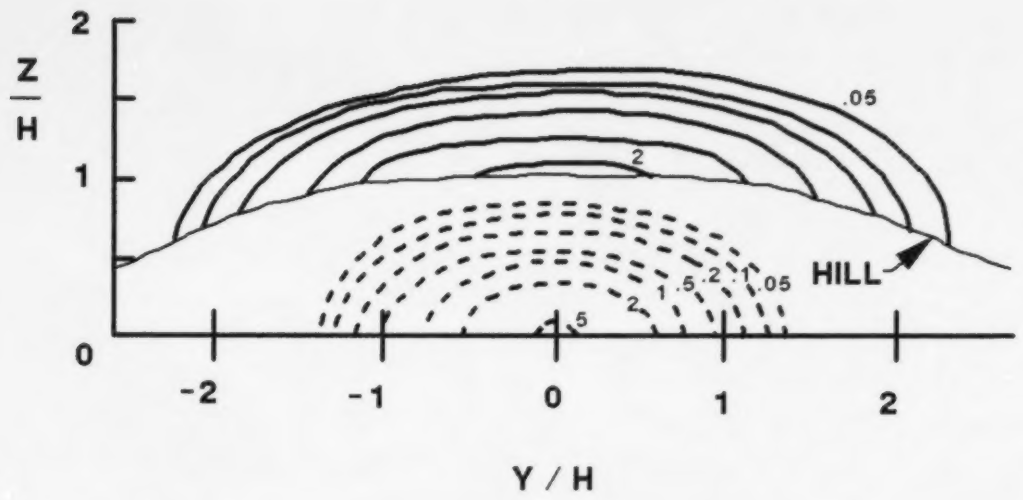

Figure 12. Plume cross sections measured in presence (———) and in absence (– – –) of axisymmetric CCB model at $x=0$ (hill center). $H_s/h=0$, $x_s/h=-6$, $y_s/h=0$.

3.2 Supplemental Modeling of Complex Terrain

In addition to the modeling done in direct support of the CTMDP, numerous other complex terrain studies were conducted at the FMF, primarily in response to envisioned needs of and direct requests from the OAQPS, the regulatory arm of EPA. These ranged from generic studies attempting to understand the fundamental physics of flow and diffusion in neutral and stable environments to a practical demonstration to determine the good-engineering-practice stack height for a specific power plant located in complex terrain. Whereas the studies done in direct support of the CTMDP were primarily concerned with plume impingement from upwind sources and focussed primarily on strongly stable conditions, the supplemental studies were broader ranging, for example, including sources on the tops and lee sides of hills, perhaps a broader range in stability from strongly stable to neutral, and investigation of similarity criteria – rules to ensure that the behavior of the flow in the laboratory simulates that in the real world. An example of the latter is the *Guideline for Fluid Modeling of Atmospheric Diffusion,* prepared by Snyder (1981) in response to a request from the OAQPS. In several cases, studies that were initiated through the CTDM developers were subsequently enlarged upon and expanded so as to be useful to the modeling community at large. Hence, in many cases, studies could have been described as supplemental (this section) or in direct support of the CTMDP (Section 3.1). The choices have been somewhat arbitrary.

One of the important overall goals in this effort was to ascertain what circumstances lead to the largest ground-level concentrations, *i.e.*, are larger glc's expected when the plume from an upwind source impinges on a hill or when the source is downwind of that hill such that the plume is caught in a recirculation region and downwashed to the surface? Which are likely to lead to larger glc's, two-dimensional or three-dimensional hills? Stable conditions or neutral conditions? In each of these circumstances, what order of magnitude of surface concentrations may be expected?

Neutral-Flow Wind-Tunnel Studies

A simple method used to intercompare effects of terrain on the maximum glc and to determine worst-case conditions is through the terrain amplification factor, as mentioned in Section 3.1. Again, the terrain

amplification factor, A, is defined as the ratio of the maximum ground-level concentration occurring in the presence of the terrain feature, χ_{mx}, to the maximum that would occur from the same source located in flat terrain, χ°_{mx}, *i.e.*, $A = \chi_{mx}/\chi^{\circ}_{mx}$. This definition is useful only for elevated sources, of course, because for ground-level sources, the maximum surface concentration occurs at the source itself.

Numerous neutral-flow wind-tunnel studies have been conducted at the FMF on diffusion over two-dimensional terrain features: (a) a ramp with a slope of 14° followed by a plateau (Snyder and Pendergrass, 1980; Pendergrass and Arya, 1983; Pendergrass and Snyder, 1987), (b) a bell-shaped hill with a maximum slope of 12° (Courtney, 1979; Courtney and Arya, 1980), (c) a steep triangular ridge with a slope of 63° (Arya and Shipman, 1981; Arya et al, 1981), (d) a series of smooth shaped hills of various slopes (Khurshudyan *et al*, 1981; Capuano, 1983; and Lawson and Snyder, 1985, 1987) and (e) a valley formed between two ridges of sinusoidal cross section (Lee et al, 1981). Three studies have been performed to determine the effects of the crosswind aspect ratio of a triangular ridge on dispersion from nearby sources. As mentioned in Section 2, Snyder and Britter (1987) investigated surface concentrations on the ridges from upwind sources. (Note that the work was done in 1979, much earlier than the publication date, so that the results were available, indeed, *used* in the development of a forerunner to CTDM.) Castro and Snyder (1982) extended the study by measuring the sizes and shapes of the recirculation regions downwind of these hills of various crosswind aspect ratio, and by measuring the concentration fields resulting from sources placed at various downwind locations. Recently, Castro and Snyder (1987a) have further extended this work to include the case when the approaching wind is not perpendicular to the long axis of the hill. This allows one to use the wind-tunnel data to estimate the effects of long-time-scale wind meander. Other generic three-dimensional hill studies included: (a) conical hills with slopes of 26.5° and 17.5° with sources located at the hill top or at the downwind base (Gadiyaram, 1984; Arya and Gadiyaram, 1986) and (b) the axisymmetric CCB model with downwind sources (Lawson and Snyder, 1985, 1987). These various studies were summarized through publications at various stages by Thompson and Snyder (1981, proceedings published 1985a) and Snyder (1983a, 1983b, 1984). Only a broad overview and a few typical results will be presented here.

Table 1 shows the terrain amplification factors for the cases listed above, in order of decreasing *A*. From the standpoint of a fixed stack height, the worst location for a source appears to be just downwind of a two-dimensional ridge. Downwind sources generally result in larger glc's because of the excess turbulence generated by the hills and because the effluent is generally emitted into a low speed region where the streamlines are descending toward the surface. Maximum *A*'s are considerably larger than those downwind of three-dimensional hills. A probable cause of this effect is that, in three-dimensional flows, lateral and vertical turbulence intensities are enhanced by roughly equal factors, whereas in two-dimensional flows, the lateral turbulence intensities are not enhanced as much as are the vertical turbulence intensities (because of the two-dimensionality). Since the maximum glc depends upon the ratio σ_z/σ_y (Pasquill, 1974), we may expect the *A*'s downwind of two-dimensional hills to be larger than those downwind of three-dimensional hills. Also, the sizes of the recirculating cavity regions downwind of three-dimensional hills are generally much smaller than those downwind of two-dimensional ridges.

TABLE 1. SUMMARY OF TERRAIN AMPLIFICATION FACTORS FOR SOURCES IN THE VICINITY OF HILLS IN NEUTRAL FLOW

Source Location	Hill Type	A
Downwind	Two-Dimensional	10-15
Downwind	Three-Dimensional	5-6
Upwind	Three-Dimensional	2-4
Upwind	Two-Dimensional	1-3
Top	Two-Dimensional	0.5-1

With regard to upwind sources, terrain amplification factors are larger for three-dimensional hills because, in such flows, streamlines can impinge on the surface and/or approach the surface more closely than in two-dimensional flows.

Table 1 listed approximate values of maximum terrain amplification factors that were found in the various situations. They are useful only for scoping a particular problem or for finding the worst possible situation.

They do not provide practical estimates for use by, say, an air pollution meteorologist in determining the maximum glc resulting from a particular power plant or for determining the best location for that plant. For that purpose, the concept of a "window" of excess concentrations, as introduced by Hunt *et al* (1979) is more useful. For any given plant location (say, upwind of the hill), there is a *limited* range of stack heights H_s for which a *significant* amplification of the glc will occur. (For sake of argument, we will here define significant as a factor of 2.) This amplification can occur only if the position of the maximum glc lies on or near the hill surface. For small H_s, χ_{mx} will occur upwind of the hill and thus be little influenced by the hill, so that A ($\equiv\chi_{mx}/\chi^{\circ}_{mx}$) will approach unity. If H_s is too large (for example, $H_s \gg h$, the hill height), χ_{mx} will lie well beyond the hill and A will again approach unity. In either case, there is little amplification. These "windows" of critical H_s values have been measured by Lawson and Snyder (1985, 1987) for two typical hill shapes that might be found in the real world, one axisymmetric, the other two-dimensional. The results are shown in Figure 13. The 1.4-window, for example, extends to about 14*h* upstream, 10*h* downstream, and as high as 1.8*h* in the vertical for the axisymmetric hill. For the two-dimensional hill, this 1.4-window extends about 8*h* upstream, 15*h* downstream, and as high as 2.2*h* in the vertical.

Such contour maps as provided in Figure 13 can be very useful for the practitioner. Once an acceptable terrain amplification factor (or "excess concentration") is decided upon, it is a simple matter to trace the window on the contour map to determine the area (plant location and/or stack height) to be avoided. Conversely, from such maps, the likely maximum glc for a potential site and stack height can be estimated. The use of terrain amplification factors simplifies the application of these data to full-scale situations. The expected maximum glc in flat terrain is calculated (from mathematical models or standard curves), then the concentration in the presence of the hill is simply the product of this quantity and the TAF. This study was initiated through a request from the EPA Office of Air Quality Planning and Standards (OAQPS) to aid in the decision-making process with regard to the promulgation of the Stack Height Regulations under the Clean Air Act, and the data were provided to OAQPS much earlier than the publication dates shown.

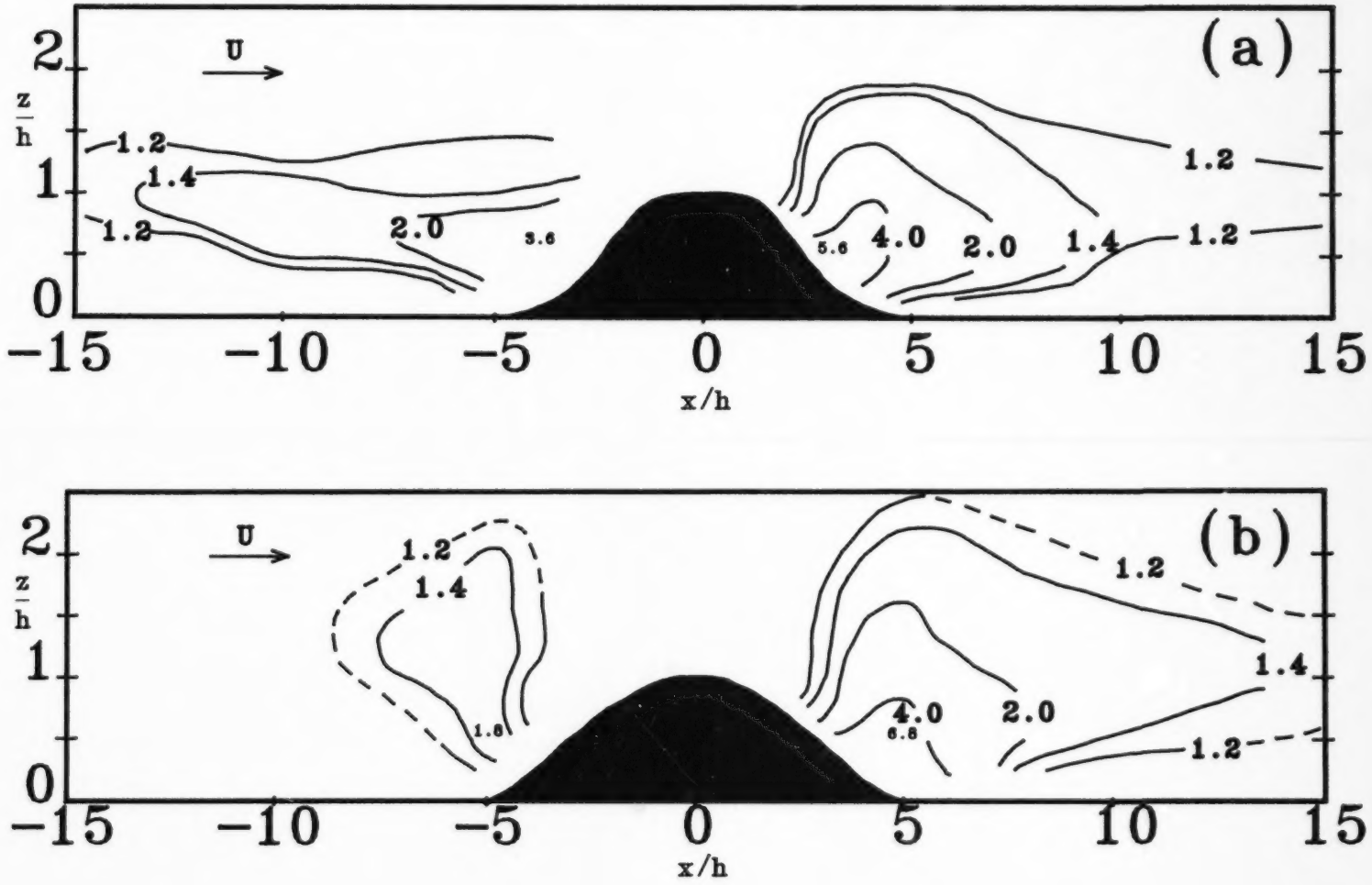

Figure 13. Contours of constant terrain amplification factors over (a) axisymmetric hill and (b) two-dimensional ridge. Note that vertical scale is exaggerated by a factor of 3.

Subsequent to the idealized study described above, the OAQPS requested the FMF to conduct a study demonstrating the application of the fluid modeling approach to the determination of good-engineering-practice (GEP) stack height for a power plant in complex terrain, *i.e.*, to provide an example study/report for industry to follow in the conduct of a GEP determination. The site chosen for this demonstration was the Clinch River Power Plant in southwestern Virginia, and a 1:1920 scale model of the surrounding terrain was constructed. Measurements were presented (Snyder and Lawson, 1985b) that described the simulated atmospheric boundary layer structure, plume-dispersion characteristics in that boundary layer, and the maximum glc of effluent downstream from the plant, both in the presence of all significant terrain surrounding the plant and in the absence of "nearby" upwind terrain. Analysis of the maximum glc showed that, in this case, a stack height of 326m met the GEP criteria under 50% load conditions, *i.e.*, the nearby upwind terrain effected an increase of 40% in the maximum ground-level concentration. This study followed the general guidance set forth in the *Guideline for Fluid Modeling of Atmospheric Diffusion* (Snyder, 1981) and the specific recommendations set forth in the *Guideline for Use of Fluid Modeling to Determine Good Engineering Practice Stack Height* (EPA, 1981) and the *Guideline for Determination of Good Engineering Practice Stack Height (Technical Support Document for the Stack Height Regulations,* Revised Draft) (EPA, 1985).

Stably Stratified Towing-Tank Studies

Lamb and Britter (1984) conducted a combined numerical and laboratory study of so-called shallow water flow over an isolated hill. They showed how certain geometrical and flow parameters affect the tendency of a fluid to flow around rather than over an obstacle in the case of a homogeneous single layer fluid, *i.e.*, simulating the atmospheric condition of an elevated step inversion. A series of numerical experiments was conducted using a finite-difference model. Measures were suggested for quantitative assessment of the tendency of the fluid to flow around the obstacle as a function of the relative hill height and the Froude number. The laboratory experiments examined the motions of two superposed homogeneous layers of fluid past a conical hill in the towing tank. The resulting motions were found to agree with the results of the numerical experiments and extended the understanding

gained from them. Flow visualization techniques were used to demonstrate the impingement of the interface on the obstacle, and its dependence on flow speed and hill height.

Another numerical model was acquired and implemented at the FMF for comparison with laboratory results. The numerical model was originally developed by Mason and Sykes (1979); it integrates the Navier–Stokes equations for incompressible stratified flow using a finite-difference scheme. Direct comparisons were made between the results of this model and laboratory experiments for density-stratified flow around the idealized axisymmetric CCB model by Rottman *et al* (1987) for three specific experimental arrangements. First, a small towing tank was used in which both the Reynolds number and Froude number were matched exactly with the numerical model. This provided an overall assessment of the accuracy of the approximations made in the numerical model. Second, the large towing tank was used in which mean plume trajectories were measured and compared with particle paths computed through the numerical model. Third, some comparisons were made with wind-tunnel measurements of the flow structure over the hill. In general, the numerical model qualitatively reproduced the experimental results on the flow structure.

Whereas the following area of investigation is not directly related to complex terrain, it is included here because it played an important (and somewhat controversial) role in the CTDM formulation. This is the area of describing the effects of stable stratification on turbulent diffusion or, put another way, estimating vertical plume growth in the nighttime stable boundary layer. Experiments were conducted (Britter *et al*, 1983) in which a grid was towed horizontally along the stratified towing tank. The vertical velocity fluctuations produced near the grid were reduced under strong stratification by up to 30%, but the decay rates of the turbulent velocity fluctuations were found to be unaffected by the stratification over a considerable distance downstream. Turbulent diffusion from a point source located downstream of the grid was also measured. The lateral plume widths were found to be largely unaffected by the stratification and grew with the 1/2-power of time. The vertical plume growth, however, was found to reach an asymptotic limit. These results were largely in agreement with the theoretical models of Csanady (1964) and Pearson *et al* (1983), but in contradiction to the theory and limited data of Venkatram *et al* (1984). The latter data suggest a continuous

vertical plume growth (for large times), but the measurements did not, in fact, extend very far downwind (maximum downwind distance of about 1 km).

Further grid-turbulence studies were done in the towing tank with the aim of investigating internal wave effects and providing guidance on the partitioning of wave and turbulence energies in stably stratified flows (Rottman and Britter, 1986). The results suggested that the fraction of available turbulent kinetic energy that is converted to potential energy, commonly referred to as the mixing efficiency, increases monotonically with increasing stability, and there is some indication that this mixing efficiency approaches a constant as the flow becomes strongly stable.

A cooperative project was completed with the Los Alamos National Laboratory to examine the conditions under which flushing of a valley between two ridges will occur, *i.e.*, to answer the question of when a stable crosswind will sweep the valley clean and when the flow will separate from the top lee side of the first ridge, reattach at the top windward side of the second ridge, and thus form a nearly stagnant region in the valley beneath. In this series of towing-tank studies, three experimental parameters were varied: the steepness of the ridge/valley slopes (40°, 27° and 13°), the separation distance between the ridges, and the Froude number that characterizes the stability of the crosswind. In broad terms, the characteristics of the flow between the ridges may be explained using criteria for boundary-layer separation from the lee side of a single ridge. The downstream ridge appears to induce separation from the lee side of the upstream ridge only when it is steep-sided (Lee *et al*, 1984a,b, 1986, 1987). As an offshoot of this work, the conditions conducive to the onset of severe downslope winds on the lee sides of mountains was investigated (Rottman and Smith, 1987). The results showed that an intrusion (breaking wave - associated with severe downslope winds) existed when the Froude number based on the ridge height was in the range $0.2 \leq F \leq 0.6$ for a steep-sloped ridge (maximum slope 40°) and $0.2 \leq F \leq 1.1$ for a low-sloped ridge (13°).

An overview of fluid modeling of pollutant transport and diffusion in stably stratified flows over complex terrain was provided for *Annual Review of Fluid Mechanics* by Snyder (1985).

4. SUMMARY

The EPA Fluid Modeling Facility has conducted a wide range of laboratory studies and a limited amount of numerical modeling of flow and diffusion in association with the Complex Terrain Model Development Program. The goal of the CTMDP is the development of a dispersion model valid in complex terrain, with emphasis on plume impaction on nearby hills during nighttime stable conditions. Work at the FMF prior to the inception of the program provided the basic framework for the model – the dividing-streamline concept – and the focal point around which to design the field program.

Throughout the course of the CTMDP, the FMF interacted vigorously with the model developers by providing support in various ways. Early work provided direct support in planning the details and strategies of the field experiments and solidifying and testing the limits of applicability of the dividing-streamline concept. Later work included exercises of "filling in the gaps" in the field data, furthering the understanding of the physical mechanisms important to plume impaction in complex terrain and in stably stratified flows in general, and testing the ability of the laboratory models to simulate full-scale field conditions. And, as the needs arose, the FMF tested various modeling assumptions, concepts, and hypotheses and provided data for "calibration" of various parameters within the CTDM model.

Simultaneously, the FMF responded to the needs of the regulatory arm of EPA, the Office of Air Quality Planning and Standards, by providing guidance concerning expected terrain effects and by providing a demonstration study – an example for industries to follow in conducting good-engineering-practice stack height determinations in complex terrain. Also, a broad range of supplemental studies was conducted, expanding and enlarging upon the specific requests of the OAQPS and the CTDM model developers to provide information of general use to the scientific and air pollution modeling communities. Many of the data sets generated in the course of this program have been provided to and used by various groups (nationally and internationally) in the development, testing and evaluation of complex terrain dispersion models.

The most significant contributions included (1) the conceptual framework for the mathematical model (*i.e.*, the division of the flow–field into two regimes, a lower layer below the dividing–streamline height which flows in essentially horizontal planes around the hill, and an upper layer above the dividing–streamline height which is treated as modified potential flow over a cut–off hill) and the detailed experimental validation and establishment of limits of applicability of these concepts, (2) verification of the integral formula for the height of the dividing streamline – this allowed computations of the dividing–streamline height under arbitrary approach–flow conditions, including shear in the approaching wind–speed profile and nonlinear temperature gradients, (3) demonstration of the extreme sensitivity of surface concentration patterns to wind direction under strongly stratified conditions, (4) measurements of plume deflections and deformations over hills in neutral flow – these permitted adjustment of the T–factors in CTDM and resulted in substantial improvements in the CTDM predictions, and (5) the introduction of the concept of "windows of excess concentration" and measurements of terrain amplification factors – these provided simple and practical methods for estimation and intercomparison of effects of terrain and source locations on maximum ground–level concentrations that may result from sources placed in the vicinities of hills.

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